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An Analysis of Nondestructive Evaluation Techniques for Polymer Matrix Composite Sandwich Materials

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Abstract

Structural sandwich materials composed of triaxially braided polymer matrix composite material face sheets sandwiching a foam core are being utilized for applications including aerospace components and recreational equipment. Since full scale components are being made from these sandwich materials, it is necessary to develop proper inspection practices for their manufacture and in-field use. Specifically, nondestructive evaluation (NDE) techniques need to be investigated for analysis of components made from these materials. Hockey blades made from sandwich materials and a flat sandwich sample were examined with multiple NDE techniques including thermographic, radiographic, and shearographic methods to investigate damage induced in the blades and flat panel components. Hockey blades used during actual play and a flat polymer matrix composite sandwich sample with damage inserted into the foam core were investigated with each technique. NDE images from the samples were presented and discussed. Structural elements within each blade were observed with radiographic imaging. Damaged regions and some structural elements of the hockey blades were identified with thermographic imaging. Structural elements, damaged regions, and other material variations were detected in the hockey blades with shearography. Each technique's advantages and disadvantages were considered in making recommendations for inspection of components made from these types of materials.

1. Introduction

Under the former Aviation Safety program at NASA Glenn Research Center, structural sandwich materials with a foam core between two polymer matrix composite (PMC) material face sheets were investigated for use in engine fan containment systems. Impact damage in these materials is of interest as their physical properties degrade with damage. Therefore, damage detection and material characterization are critical to evaluating component manufacture practices and for inspecting components in routine maintenance throughout service life. Proper damage detection and material characterization require the development and improvement of existing nondestructive inspection techniques for use with sandwich materials. Aerospace components made from sandwich materials were not readily available due to the high manufacturing costs and concerns with proprietary manufacturing practices. Since these structural materials have additional applications, such as hockey blades, where impact damage is also of interest and components were readily available, hockey blades with PMC material face sheets sandwiching foam cores were investigated with various nondestructive evaluation (NDE) methods. A single flat panel having a foam core between two PMC material face sheets also was obtained and investigated for this study.

The objective of this research was to determine which NDE method or methods are optimal for investigating damage (delaminations, cracks and foam core damage) in sandwich materials composed of PMC face sheets with a foam core. A flat sandwich sample and hockey blades used in actual National Hockey League (NHL) hockey games composed of different types of structural sandwich material were analyzed with multiple NDE techniques (pulsed thermography, real-time x-ray, and shearography) to investigate damage detection capabilities and make inspection recommendations for these materials. Results from the NDE methods were compared with each other and with those from visual inspection.

In addition to types of damage detected, technique costs, ease of use, training requirements, safety requirements, surface preparation, inspection time, and capabilities in detecting structural elements inherent to the material were considered. Recommendations are provided in a tabular form for the user to select methods that are appropriate for specific applications. As a result of the analysis, NDE methods that are most promising for use with the hockey blades and the flat sandwich panel were recommended for future inspection purposes.

2. Experimental

2.1 Material Specifications

The hockey blades were made from a structural sandwich material with PMC face sheets and a foam core. The face sheets were approximately 1 mm thick and consisted of a triaxially braided carbon fiber and epoxy resin laminate. The core thickness varied and consisted of Acrylonitrile Butadiene Styrene (ABS) plastic, foam material or a combination of both ABS and foam materials. Due to the variation in core thickness, the full thickness of each blade varied from 5 to 8 mm from the blade tip to the joint where the blade meets the stick. Although twenty-six blades were evaluated, the results from four representative hockey blades that were used in play and have damage due to impact are presented in this paper. Two blades had extensive damage that was visible from the surface: one with a large delamination extending over half the blade (fig. 1) and the other with a crack through the thickness of the foam and one of the face sheets (fig. 2). The delaminated blade shown in figure 1 also contained a crack in the foam core only. None of the foam adhered to the face sheets in the delaminated region. Both cores had ABS plastic along the bottom edge with the remainder of the blade containing foam. The two remaining blades had differing internal structures and less obvious visual damage. One of the blades contained only the ABS plastic with the center portion of the plastic having a honeycomb structure. The other hockey blade consisted primarily of foam with ABS plastic material along the bottom edge of the blade. These two blades contained delaminations at their tips.

The flat panel used to investigate damage into the foam core had PMC face sheets and a foam core. The face sheets were 2 mm thick on the side closest to the foam damage and 1 mm thick on the side opposite the foam damage. Both face sheets consisted of a triaxially braided carbon fiber and epoxy laminate. The full thickness of the flat panel was constant at 9 mm. A schematic of the panel is shown in figure 3. The 1.5 in. wide edge of the panel consisting of the sandwich material was the region of interest in this study, while the bottom 2.5 in. consisted of the PMC material only. This panel was cut from a larger panel to reveal an exposed edge of the sandwich region in order to make a region of known damage. To simulate damage in the foam core, a knife was used to create planar damage in the core as shown in figures 3 and 4. A small amount of foam remained on the surface of the face sheet.

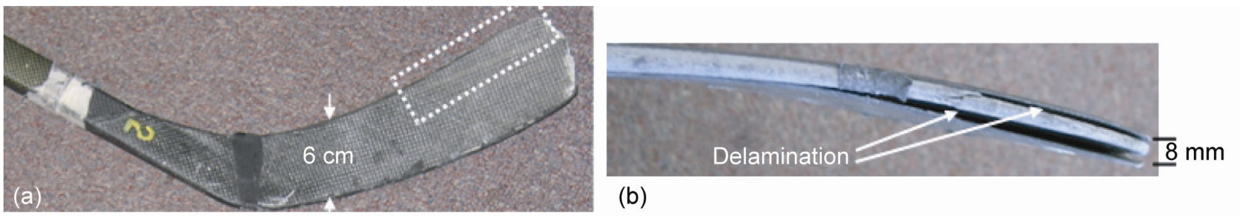

Figure 1.—Photographs of a hockey blade with a delamination extending over approximately half the blade: (a) an overall image of the hockey blade and (b) a side view from the upper right hand side of the blade illustrating the delamination.

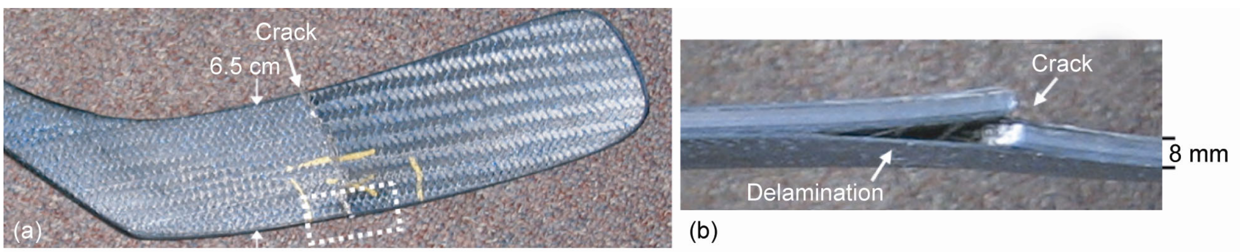

Figure 2.—Photographs of the hockey blade with a crack through the thickness of the foam and one of the face sheets: (a) an overall image of the hockey blade illustrating the location of the crack and (b) a side view from the bottom of the blade depicting the morphology of damage near the crack.

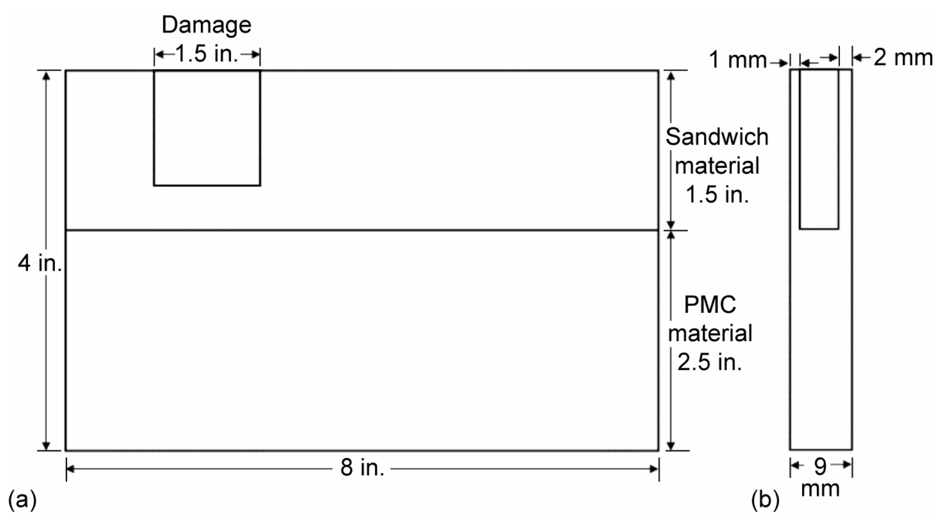

Figure 3.—Schematics of the flat panel with sandwich material depicting the locations of the sandwich material and the foam core damage. (a) Top view of the sample. (b) Side view of the sample.

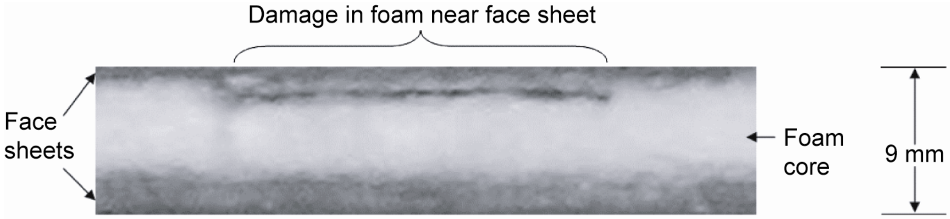

Figure 4.—A side view of the sandwich material in the flat panel illustrating the intentional damage inserted into the foam core.

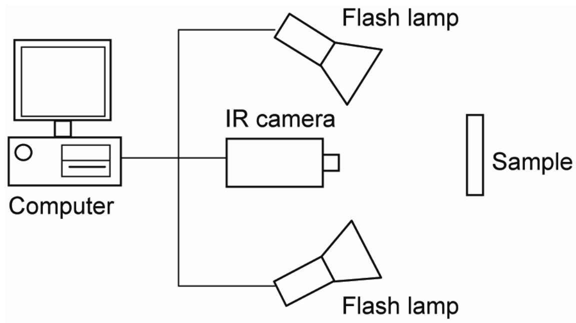

Figure 5.—Pulsed thermography experimental setup.

2.2 Pulsed Thermography

Pulsed thermography is a full field nondestructive evaluation technique for detecting subsurface flaws and material variations (refs. 1 to 3). The setup for the commercially available pulsed thermography system utilized in this research is depicted in figure 5. Two high energy xenon flash lamps, placed to provide a uniform heat distribution across the surface of a component, produce a 1.8 kJ flash with a 2 ms duration. A high speed, 640 by 512 pixel InSb focal plane array infrared camera monitors the thermal response of the component of interest over time. A smaller portion of the focal plane array may be utilized to increase the acquisition rate. For this study, a 320 by 256 pixel portion of the full focal array was utilized with a frame acquisition rate of 120 Hz. Each sample was placed in front of the thermal camera so it filled the active focal plane. Flash initiation, data collection, storage, and processing were performed with a commercially available software package loaded onto the acquisition computer. The software acquires a data cube which consists of a sequence of thermal images starting just prior to the flash event. Each image represents the thermal response of the sample surface at a different point in time. The data cube acquired from the hockey blades consisted of 374 images (or a time length of 3.11 sec) with image resolution of approximately 0.85 mm/pixel. The data cube acquired for the flat sandwich panel contained 900 images (or a time length of 7.3 sec) with image resolution of approximately 0.72 mm/pixel.

Under uniform one-dimensional heat flow, analysis of a thermal response signal is based on the mathematical expression for surface temperature, T, of a specimen subjected to an instantaneous heat pulse,

$$T = \frac{Q}{e(\pi t)^{0.5}}$$

where Q is the input energy, t represents time, and e denotes the effusivity of the sample (refs. 2 to 3). Effusivity, a measure of the ability of a material to increase its temperature due to a given energy, is the square root of the product of thermal conductivity, density, and specific heat of the material of interest. The natural log of the above equation is

$$\ln(T) = \ln\left(\frac{Q}{e}\right) - 0.5\ln(\pi\, t)$$

In the logarithmic domain, the thermal response is linear with a slope of –0.5 (refs. 2 and 3). The time at which the function deviates from this linear behavior corresponds to the transition from ideal one-dimensional conductive cooling behavior to two-dimensional, lateral heat flow due to the presence of a subsurface defect or foreign material. The logarithmic time dependence of each pixel in a thermal image can be approximated by an nth-order polynomial function. After the coefficients, a_i, of the relationship are calculated for each pixel, the original thermal image is reconstructed based on the relationship

$$T(t) = \exp\left[\sum_{i=0}^{N} a_i \left[\ln(t)\right]^i\right]$$

The reconstructed data offers many advantages, such as a reduction of noise, an optimization of storage and data handling requirements, and allowing for the calculation of instantaneous derivatives to provide additional or more easily interpreted information (ref. 3). First derivative images are presented in this paper. In each grayscale image, white represents a faster cooling rate while black represents a slower cooling rate relative to the surrounding region. Early in time, white will appear for a region with thermally conductive material below the surface while black will appear for regions with insulating material, such as air associated with a void or delamination. Later in time, this trend reverses when the thermally conductive material is cool and the heat trapped at the surface moves into the cooler regions causing the area to cool more rapidly relative to the surrounding region.

2.3 Real-Time X-ray

The real-time x-ray system, depicted in figure 6, has a resolution of approximately 3.5 LP/mm. X-rays were generated with a 120 kV microfocus x-ray tube at a voltage of 60 kV and current of 0.37 mA. At this power level, the focal spot size was approximately 20 µm. The source to object distance was approximately 47 in. (119.4 cm). The object to detector distance was 27 in. (68.6 cm), resulting in a magnification factor of 1.57. The unabsorbed x-rays that pass through a component are measured to create an image. Instead of using film, the real-time x-ray system utilizes an image intensifier with a scintillating screen to convert x-rays to a visible image. The resulting image is viewed using a digital CCD camera. The digital camera is interfaced with computer software developed to capture, process and store the x-ray image. Interpretation of the real-time x-ray image is opposite that of a conventional x-ray film image. Dark regions correspond to higher density areas of the sample, while lighter areas in the image correspond to a lower density.

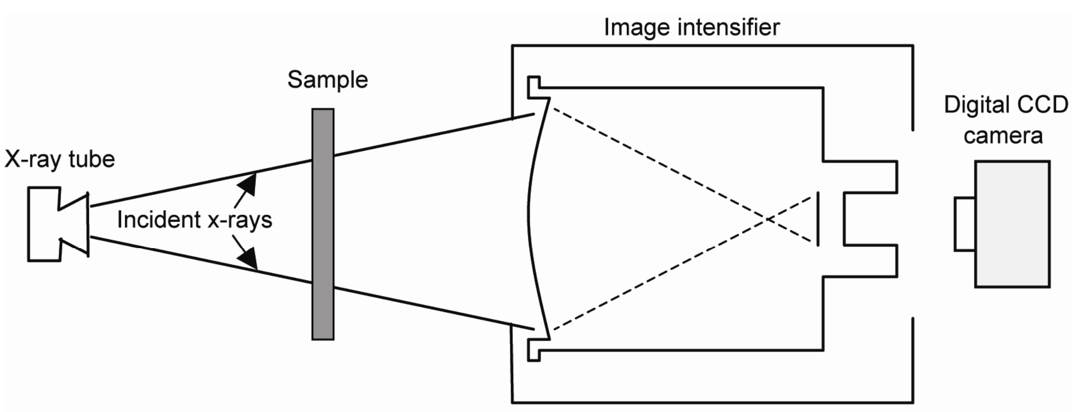

Figure 6.—Schematic of the real-time x-ray system utilized for this study, illustrating the image intensifier and digital camera in place of film as a detector.

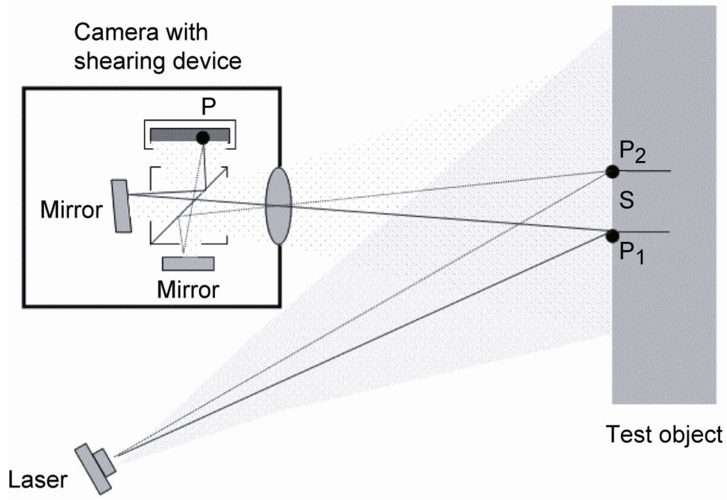

Figure 7.—Schematic of the shearography system used to collect data from the hockey blades. Two points, P_1 and P_2, on the test object are mapped to a single point, P, in the shearography image.

2.4 Digital Shearography

Shearography (also known as Electronic Shearing Speckle Interferometry) is a laser based, full field, nondestructive evaluation technique that detects discontinuities that alter the strain distribution and weaken a structure (refs. 4 and 5). The schematic in figure 7 illustrates the test setup for shearography. The test object is illuminated with a point source of laser light and is depicted with an image shearing camera. The camera produces a pair of laterally sheared images in the image plane. The effect of shearing is to map two points on the test object, at a shearing distance, s, apart, to a single point in the image plane. For this study the shearing distance was 0.5 cm. When the object is deformed, the relative displacement between the interfering points induces a relative phase change between the interfering rays. Comparing images (or speckle patterns) before and after inducing stress produces a full field image of the object's surface strain. Strain concentrations are depicted with a 'fringe' pattern which represents the spatial derivative of displacement with respect to the direction of separation (or shearing).

A variety of methods can be used for stressing when comparing two states of deformation in a test object. Pressurization, partial vacuum stressing, thermal stressing, and vibration excitation are some of the most common methods employed. For the hockey blades, thermal stressing was utilized. The surface of the hockey blades was heated with a heat gun for 20 seconds. A reference image was captured after any thermal currents disappeared from the field of view, typically 2 to 5 minutes after heating. This image represents the deformed, stressed state. Then, a comparison image was captured after waiting 1 minute for the sample to cool. These two images are then subtracted from one another to create the final shearography image like the ones presented in this paper. For the flat sandwich panel vacuum stressing was utilized. Images were acquired before and during depressurizing a vacuum chamber by approximately 0.5 psi. The exposed edges of the panel were sealed with tape prior to testing.

3. Results

The various NDE methods were able to detect structural elements within the hockey blades as well as damage resulting from in play use. In addition, damage in the foam core of the flat sandwich panel was detected. In the results that follow, structural elements will be considered first in section 3.1 while defects and damage will be discussed in section 3.2. Delaminations, lateral cracks and damage in the foam core will be discussed in sections 3.2.1, 3.2.2, and 3.2.3, respectively.

3.1 Structural Elements

In this paper structural elements refer to elements that are integral to the structure of the hockey blade components and do not represent defects in the component. The structural elements inherent to the sandwich materials that were detected with nondestructive evaluation include the presence of fibers in the face sheets and foam core, structural staples, the fiber architecture of the triaxial braid, and material differences such as variances in the type of foam core utilized in the hockey blades (e.g, solid foam core or ABS plastic with a honeycomb core). Some structural elements, such as the surface fiber architecture, were optically visible while the structural staples, the core material, and material variations were not.

X-ray was able to detect structural elements that affected absorption characteristics in a component. Figure 8 represents two x-ray images from two individual hockey blades. Figure 8(a) is an image from the blade with a crack through the foam core and one of the face sheets while figure 8(b) depicts a composite image of one of the hockey blades with a honeycomb ABS plastic core. The blade with the honeycomb core was used in play and had a delamination at its tip. As shown in the images, x-ray detected many structural elements including structural staples (fig. 8(a)), fine glass fibers at the foam core and face sheet interface (fig. 8(a)), the honeycomb structure in the core (fig. 8(b)), and material differences between the foam core and the ABS plastic core at the blade edge depicted as a grayscale color change (fig. 8(a)). Both images also illustrate the axial fibers along the length of the hockey blade. It should be noted that neither image depicts the delaminations in these two blades. The x-ray image in figure 8(a) is from the cracked blade depicted in figure 2, which had a delamination on the backside of the hockey blade.

Pulsed thermography was able to detect structural elements that alter the flow of heat from the front surface to the back surface of a component. Surface conditions, such as the triaxial braid, that were visible at the surface were identified in the thermography images. Also, subsurface sandwich material differences between the foam and ABS plastic material were observed in the thermography images. To illustrate thermography's capabilities for detecting structural elements, figure 9 shows thermal derivative images from the front (fig. 9(a)) and back (fig. 9(b)) of the hockey blade with a crack through the thickness of the foam core and one of the face sheets. This is the same hockey blade depicted in the x-ray image shown in figure 8(a). Sandwich core material differences are depicted with variations in grayscale contrast. The ABS plastic core along the bottom edge of the hockey blade was detected as lighter shades of gray and white, while the foam core is depicted in dark gray and black corresponding to a slower cooling rate relative to the surrounding region. The fiber architecture that is visible from the surface is detected in these images as variations in contrast as well. Figure 10 represents a thermal derivative image from the front side of the hockey blade with a honeycomb core and a delamination at the blade tip. Portions of the honeycomb core may be detected in the image with dark gray or black above the void regions. However, without a priori knowledge of the honeycomb core this structural element may go undetected from the pulsed thermography results. Elements that were not recognized in the thermal images were the structural staples and fine glass fibers in the foam and in the PMC face sheet material.

Shearography was able to detect the honeycomb structure, material differences between the foam core and the ABS plastic core materials, structural staples, and other variations that caused changes in deflections (and hence strain) at the component surface. Figure 11 illustrates some of the structural elements that were revealed in the shearography images. Figure 11(a) represents the shearography image from the hockey blade that contained a delamination that extended over half the blade. The structural information that was detected from this blade included differences in core material. The bottom edge of the hockey blade contained ABS plastic while the remainder of the blade contained a foam core. Figure 11(b) depicts the shearography results from one of the blades used in play. The core of this blade contained only ABS plastic with a honeycomb configuration which was detected as a repetitive pattern over the center of the blade. Figure 11(c) illustrates the shearography results from another blade that was used in play. The structural information depicted in this image is the structural staples and the triaxial braid fiber architecture of the composite. The fiber architecture is also visible from the surface.

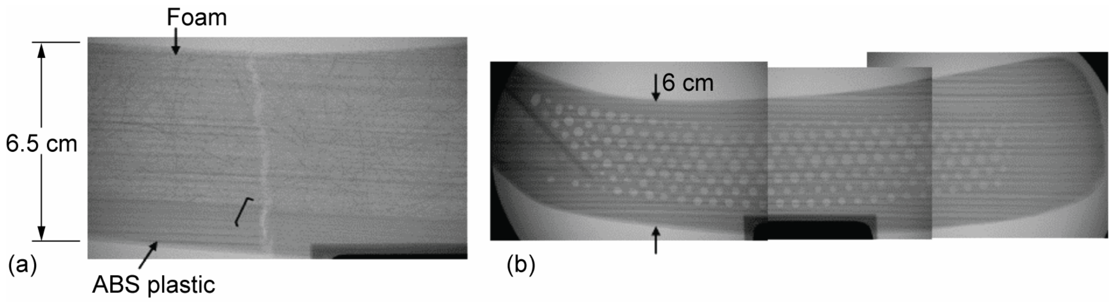

Figure 8.—X-ray images from the center of a hockey blade with a crack in the foam and through one of the face sheets (a) and a composite image of a whole blade used in play with a plastic honeycomb core and a delamination at the tip (b).

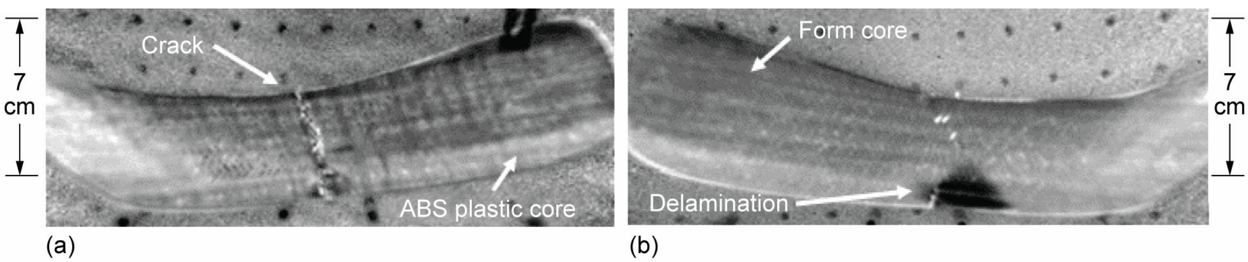

Figure 9.—Thermal derivative images from the front side (a) and back side (b) of a hockey blade with a crack through the foam and one of the face sheets illustrating subsurface material differences, surface conditions and damage detected with pulsed thermography.

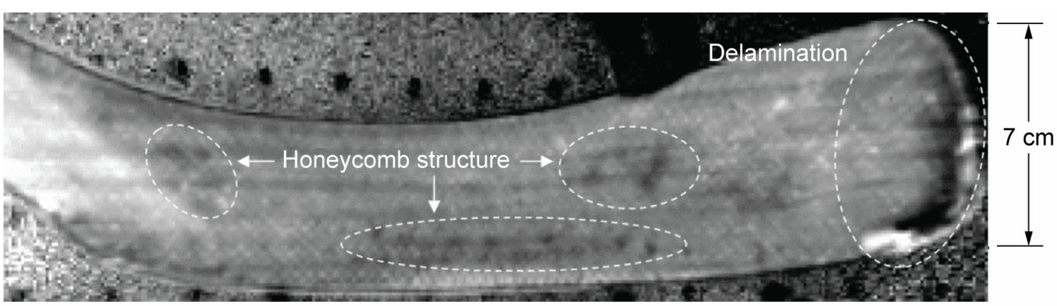

Figure 10.—Thermal derivative image from the front side of the hockey blade with the honeycomb core and a delamination at the blade tip.

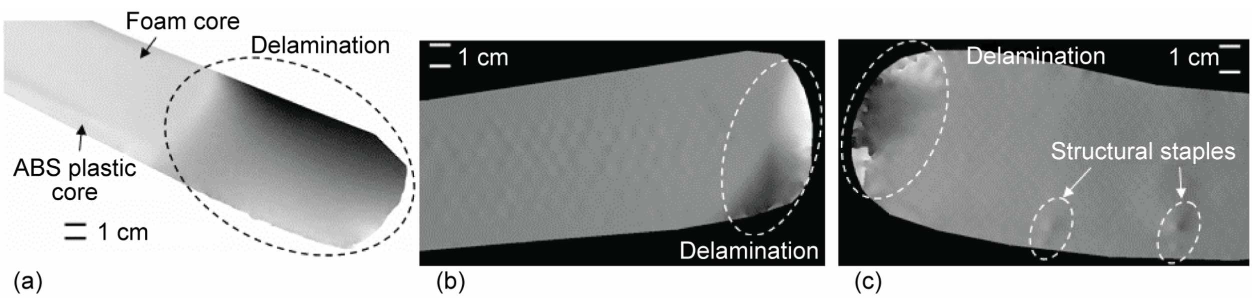

Figure 11.—Shearography images from the hockey blade with a delamination over half the blade (a), the hockey blade with an ABS plastic honeycomb core and a delamination at the tip (b), and a hockey blade containing structural staples and a delamination at the tip (c).

3.2 Defects and Damage

3.2.1 Delaminations

In this paper the term delamination refers to a planar defect that is perpendicular to the observer's line of sight. Delaminations in the PMC face sheet material or between the face sheet and the foam core were the most common types of defects found in the hockey blades.

Real-time x-ray was not able to detect delaminations in the face sheet or between the face sheet and the foam core. For example, figure 8(b) depicts an x-ray image of a hockey blade with a delamination at the blade tip which was detected with shearography (fig. 11(b)) and with pulsed thermography in figure 10. The delamination near the crack in the hockey blade depicted in figure 8(a) went undetected as well. X-ray acquires an averaged response through the thickness of a component and is sensitive to density and thickness changes. Since material was not lost due to the delamination, it went undetected.

Pulsed thermography detected delaminations in the face sheet or between the face sheet and the foam core. The delamination illustrated in figure 12 was between the face sheet and the foam core. The delaminated region appears as a dark gray or black region which corresponds to a slower cooling rate in the thermal derivative image. Figure 9(b) shows a thermal derivative image from the back side of the cracked hockey blade with the delamination. This delamination, identified in black, also occurred between the face sheet and the foam core and was not detected from the front side of the hockey blade (fig. 9(a)) with pulsed thermography. Figure 10 presents a thermal derivative image from the hockey blade with the honeycomb core and delaminations at the blade tip. The delaminations are represented by the black region at the tip of the blade.

Shearography also detected delaminations in the face sheet or between the face sheet and the foam core. Figure 11 illustrates shearography images from three blades with delaminations. Typically defects, or structurally weaker regions, are indicated with a "butterfly" pattern having alternating contrast levels over the defective region. The patterns shown in figure 11(b) and (c) over delaminated areas are most reflective of this type of damage indication. The damage in the blade depicted in figure 11(a) was extremely severe and easily detected with shearography. Although no images are presented here, shearography was also capable of detecting delaminations on the side opposite of, or furthest from, interrogation.

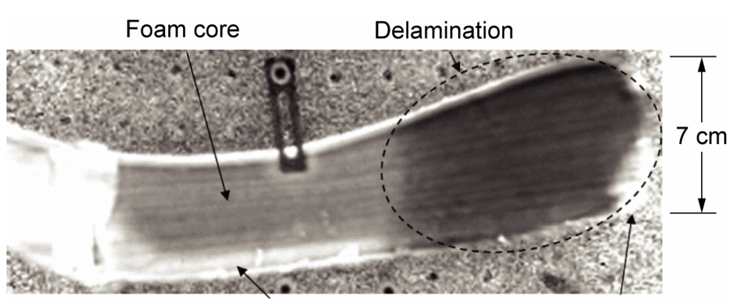

Figure 12.—Thermal derivative image from the hockey blade with a delamination between the core and the face sheet over approximately half the blade. This blade had a foam core and ABS plastic along the bottom edge of the core.

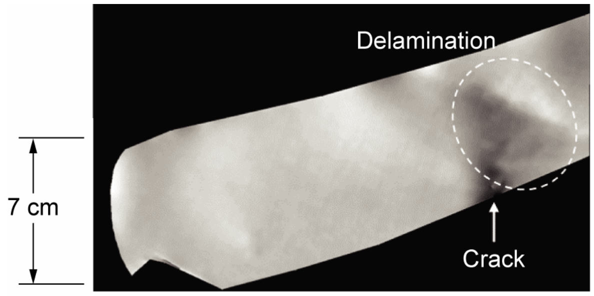

Figure 13.—Shearography results from a hockey blade with a crack through one of the face sheets and into the foam core. The crack and the delamination were detected and shown in the image.

3.2.2 Lateral Cracks

In this paper the term crack refers to a planar defect that is parallel to the observer's line of sight. Real-time x-ray detected the crack that went through one face sheet and the foam core, as shown in figure 8(a). However, a crack that was only in the foam core was not detected. The hockey blade with the delamination extending over half the blade also contained a crack that was in the foam core that went undetected with x-ray. The density of the foam may have been too low for the x-ray image to differentiate it from the surrounding air.

Figure 9 illustrates thermal derivative images from the hockey blade with a crack in one of the face sheets and in the foam core. The crack was detected in the thermal derivative image from the side with the optically visible crack, as shown in figure 9(a). From the side where the crack was not optically visible the crack was not detected. However, the response from the crack may have been masked by the response of the delamination. Also, the crack in the foam only was not detected with thermography.

Figure 13 depicts the shearography results from the blade with a crack through one of the face sheets and into the foam core. These results were acquired from the side of the hockey blade where the crack was not optically visible. The crack and the delamination were detected together in this image. The crack in the core of the hockey blade with the large delamination was not detected with shearography due to the response of the crack being masked by the response of the delamination.

3.2.3 Damage in the Foam Core

The flat panel was used to further investigate foam core damage. A thin planar defect similar to a delamination was intentionally inserted into the foam core near the interface of the face sheet. X-ray did not detect the intentional damage in the foam core. The density of the foam may have been too low for a change to be detected. In addition, x-ray is limited in its detection capabilities of planar flaws perpendicular to the direction of the x-ray beam.

Pulsed thermography also was not able to detect the damage in the foam core of the flat sandwich panel. The heat flow may have altered from being predominantly one-dimensional, flowing laterally from the front surface to the back surface through the face sheet, to being dominated by two-dimensional heat flow when it reached the back surface of the face sheet. This effect may be due to a similarity in the thermal conductivity of the air gap and the foam. Very little or no heat transferred from the face sheet to the foam core making the defect in the foam undetectable.

Shearography was able to detect the damage in the foam core as shown in the image from the flat panel in figure 14. In the image, shearography also detected the presence of sandwich material as an alternating pattern of black and white, which is often referred to as a "butterfly" pattern. This pattern indicates that the local stiffness and strength of the region with the sandwich material differs from that of

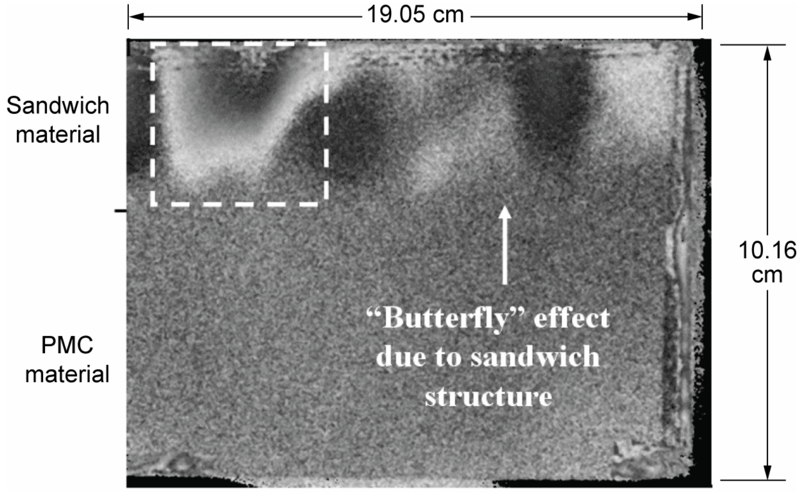

Figure 14.—Shearography results from the flat panel illustrated in figure 3 highlighting the detection of the damage in the foam core.

the region consisting of the PMC. The shearography response in the region of the panel where damage was intentionally inserted into the foam core was shown as a darker black region surrounded by a lighter white region. It is highlighted by a dashed square in the figure. Shearography also was able to detect the core damage from the opposite side of the panel.

4. Discussion

Often an integrated approach incorporating multiple NDE methods is used to achieve a complete characterization of the damage and structural information from a component. However, for a given application only a specific defect type or structural element may be of interest, making complete characterization of a component unnecessary. In recommending the best NDE approaches for sandwich materials with PMC face sheets, a number of considerations have to be taken into account. Table 1 lists the issues that were considered with respect to the full field NDE methods investigated in this particular study. Structural elements, delaminations, cracks and foam core damage refer to information within a component that is sought from the NDE method. Ideally, the method that is best suited to detect the information of interest would be selected. However, other considerations, which are listed at the top of the columns of table 1, often must be taken into account. The cost of the NDE system, ease of use and training requirements for the operator, safety requirements, surface preparation for the component, and inspection time required often have to be considered in addition to the ideal method for damage detection or material characterization. For each NDE method utilized in this study, these considerations were rated as stronger, average or weaker as indicated in table 1 and were discussed below. The table includes visual inspection for comparison purposes.

Structural elements refer to elements that are integral to the structure of a component such as the presence of fibers in the face sheets and foam core, structural staples, the fiber architecture, and material differences such as the variations in core material. Visual inspection was rated as weaker in the table as most of these elements were not observable visually. Only the fiber architecture at the surface was observable optically. Pulsed thermography was rated as average for detecting structural information. Structural elements such as the triaxial braid fiber architecture and differences in the core material were detectable with pulsed thermography, while the structural staples, fibers and the honeycomb core were less apparent or undetectable. X-ray and shearography were both rated as stronger for detecting structural elements. Both methods detected the structural staples, core material variations and the honeycomb core.

The surface fiber architecture of the composite was detected with shearography, while fibers at the face sheet and core interface were detected with x-ray only.

4.1 Defect Detectibility

The foam core damage observed in this study was intentionally inserted with a knife into a flat panel. For distinguishing damage in the foam core, visual, radiographic, and thermographic methods were all rated as weaker because the damage in the foam core went undetected by each of these methods. X-ray is not sensitive to planar defects or defects that do not alter the density, thickness, or absorption characteristics of a material. Pulsed thermography may not have detected the core damage as the heat flow may have been dominated by two-dimensional heat flow at the back surface of the face sheet due to the insulating effects of the foam core. This mechanism may have caused the heat not to transfer into the foam making the defect undetectable. Shearography was the only method that was able to detect the damage and therefore was rated as stronger.

Delaminations are planar defects perpendicular to the observer's line of sight. Visual and x-ray methods were rated as weaker for detecting these types of defects. Real-time x-ray did not detect the presence of delaminations as they do not affect the absorption of x-rays. Optically, delaminations can be detected only if they extend to the edge of a component. Pulsed thermography and shearography were both rated as stronger with respect to detecting delaminations as both methods identified delaminated regions. Pulsed thermography was successful at detecting delaminations due to the obstruction of heat flow. Shearography was able to detect delaminations as they altered the integrity of the component, hence weakening it. In addition, shearography was capable of detecting delaminations on the face opposite interrogation.

For crack detection, x-ray was rated as stronger while visual methods, pulsed thermography, and shearography were rated as average. X-ray produced a high contrast image highlighting a crack through one face sheet and the foam core. Crack detection is a well documented strength of radiographic methods since x-ray detects differences in thickness, density, and absorption characteristics due to material composition. However, it should be noted that real-time x-ray did not detect a crack that existed in the foam core only. This may be due to the density of the foam being so low that a difference could not be detected. Visual inspection and pulsed thermography detected what was visible from the surface only. Shearography detected damage, or differences affecting the component strength, around the crack.

For the hockey blades made from structural sandwich materials pulsed thermography and digital shearography were able to detect the most damage in the form of delaminations and cracks. For that reason these two methods are recommended as the best methods to evaluate damage in these components. If a single technique must be chosen for use to evaluate structural sandwich materials with PMC face sheets, digital shearography should be selected. Digital shearography has the distinct advantage of being able to detect defects within the core of sandwich structures as shown here and in the literature (refs. 4 to 6). In addition, shearography has been shown to detect damage on the opposite side from the interrogation face (refs. 4 to 6). This capability may be helpful in situations where only one side of the part is accessible for inspection. Pulsed thermography typically is not able to detect damage in the foam core of sandwich materials. In addition, to evaluate both face sheets of a component made of structural sandwich materials pulsed thermography must be used on both sides.

4.2 Economic Aspects

With respect to monetary costs, pulsed thermography and shearography had the highest costs which resulted in a rating of weaker. The pulsed thermography setup utilized in this study is valued at approximately $175,000. However, costs can vary per individual setup by varying components such as the infrared camera. The shearography system employed in this study has a cost of approximately $125,000. As with the pulsed thermography setup, costs can vary for individual systems based on specific components utilized. The x-ray system utilized in this study cost approximately $45,000 resulting in a rating of average for costs. Visual inspection is the least expensive, rated as stronger, requiring only the operator.

4.3 Ease of Use

For ease of use and training requirements, visual inspection was stronger than the other methods. However, most of the damage considered in this study was not visible. X-ray and pulsed thermography were stronger for ease of use and average for training requirements. Both x-ray and thermography require some training and educational background to operate the systems and interpret results. A trained operator should be able to use either of these two systems easily. Shearography was considered average for both ease of use and training requirements. However, the system can be arranged to optimize results for an individual application. In addition, an experienced operator would understand the subtle nuances of the technique.

4.4 Safety Aspects

Regarding safety requirements, visual methods and pulsed thermography were rated as stronger due to limited safety requirements. A minor safety concern with the pulsed thermography setup utilized in this study is the use of flash bulbs for heating. The operator should avoid looking directly at the flash bulbs when in use. Shearography was rated as average because precautions are necessary for some industry safe laser systems. However, no eye or skin protection was required with the system utilized in this study. The only precaution necessary was to avoid looking directly into the laser beam or at reflections from the laser beam. X-ray was rated as weaker with respect to safety as these methods require many safety precautions due to the effects of x-rays on the human body. For the x-ray setup utilized in this study, a room surrounded with lead was used to protect the operator from the x-rays. The operator was located outside the room with the x-ray controller unit and computer for data acquisition. The monetary cost of this room was not included in the cost estimate provided in the costs section of the discussion.

4.5 Sample Preparation

For surface preparation, visual inspection, x-ray, and pulsed thermography were rated as stronger as no surface preparation is required beyond normal cleaning for the PMC sandwich materials. Shearography was rated as average because the component surface needs to be white, either through the use of white paint or Magnaflux developer, which was used in this study. Magnaflux developer produces an opaque white coating from white developing particles in a fast drying solvent and is typically used for die penetrant testing. For materials and components with rough surfaces some residue may be difficult to remove after testing.

4.6 Inspection Time

With respect to inspection time, visual methods, pulsed thermography, and shearography were rated as stronger as the results each method was capable of detecting were acquired quickly with these techniques once initial parameters were set. With visual inspection, results can be attained immediately. For pulsed thermography and digital shearography inspection results can be attained under a minute. Although a real-time system was utilized for this study, x-ray was rated as average as more typical setups can take more time for developing x-ray film.

5. Conclusion

Hockey blades composed of structural sandwich materials were investigated with various nondestructive evaluation (NDE) methods including x-ray, pulsed thermography and digital shearography. Pulsed thermography and digital shearography were recommended as the best NDE methods to use for the types of defects exhibited in the hockey blades investigated in this study. Digital shearography was selected as the best method to evaluate structural sandwich materials with PMC face sheets due to its additional capabilities in detecting defects in the foam core and the face sheet opposite that of interrogation. A table was developed to aid in the selection of NDE methods for additional application needs and priorities. Along with the table, the recommendations will be applied to components made from structural sandwich materials having PMC face sheets and a foam core. Specifically, these results are being used to determine the optimal NDE method or methods for structural sandwich materials composed of triaxially braided PMC material face sheets sandwiching a foam core, which include structures employed in the recreational industries and for future containment systems in aircraft.

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13. ABSTRACT ***(Maximum 200 words)***

Structural sandwich materials composed of triaxially braided polymer matrix composite material face sheets sandwiching a foam core are being utilized for applications including aerospace components and recreational equipment. Since full scale components are being made from these sandwich materials, it is necessary to develop proper inspection practices for their manufacture and in-field use. Specifically, nondestructive evaluation (NDE) techniques need to be investigated for analysis of components made from these materials. Hockey blades made from sandwich materials and a flat sandwich sample were examined with multiple NDE techniques including thermographic, radiographic, and shearographic methods to investigate damage induced in the blades and flat panel components. Hockey blades used during actual play and a flat polymer matrix composite sandwich sample with damage inserted into the foam core were investigated with each technique. NDE images from the samples were presented and discussed. Structural elements within each blade were observed with radiographic imaging. Damaged regions and some structural elements of the hockey blades were identified with thermographic imaging. Structural elements, damaged regions, and other material variations were detected in the hockey blades with shearography. Each technique's advantages and disadvantages were considered in making recommendations for inspection of components made from these types of materials.

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